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Performance Evaluation of Artificial Bee Colony Based Proportional-Integral-Derivative Cascade Control System for Tanker Ship

By

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## ABSTRACT

*This paper presents the development of a cascade control system using an artificial bee colony based proportional-integral-derivative (PID) controller for automatic control of tanker ship steering system. Multi-purpose or automatic guidance, navigation and control (GNC) of ocean vehicles generally revolves around course keeping and course changing manoeuvres. In order to maintain or change a course, an efficient steering control plays an important role in the entire GNC system. Course keeping and course changing manoeuvres require efficient control algorithms capable of altering the course of the vessel with rapid and accurate response and with the hope of improving fuel efficiency and reducing wear on ship components. The GNC system often utilizes simple control algorithms such as the PID controller. The performance of the PID controller depends largely on the choice of its control gains ( $K_p$ ,  $K_i$  and  $K_d$ ). For large and unpredictable variations, the parameters of the ship's controller must be continually modified since the dynamics of the ship vary with other parameters such as speed, loading, trim, wind, waves, current, depth and other ocean conditions. In this work, a cascade control system was developed for the course keeping and course changing manoeuvres. Both the inner loop and outer loop were designed with an ABC tuned proportional, integral and derivative (PID) controllers to control the ship's course keeping and course changing. The performance of the developed controller was checked in simulation tests performed on the mathematical model of the tanker ship. To obtain reference data for comparison, genetic algorithm (GA) and ant colony optimization (ACO) based controllers were examined for the same conditions. For course keeping, the ABC based PD controller produced an improvement of 18.8% in rise time over GA based controller, and 7.7% in rise time over ACO based controller while for course changing the ABC based PD controller produced an improvement of 11.1% in rise time over GA based controller, and 13.6% in rise time over ACO based controller. The simulation was carried out using MATLAB R2015b.*

**Keywords:** course keeping, proportional-integral-derivative, cascade control and artificial bee colony

## INTRODUCTION

The automation of ship's steering control was first reported by Minorsky and Sperry in 1922. An autopilot is the ship's steering controller, which automatically manipulates the rudder to decrease the error between the reference heading angle and the actual heading angle (Sethuramalingam & Nagaraj, 2016). The purpose of an automatic ship steering control system is to

minimize the increase of resistance in a wide sense under the disturbance of wind or waves in the ocean. The early autopilots, which are of pure mechanical construction, provided only a very simple steering action. An autopilot has two major tasks: course keeping and course-changing. The former is the steady state heading regulation used to keep the ship on a desired course against environmental disturbances caused by wind, waves, and currents. The latter is the heading control in the transient state that changes the ship's original course (Arie *et al.*, 1986). The performance of autopilots has greatly improved since the introduction of the proportional-integral-derivative (PID) algorithm, and until recently, all commercially available autopilots were based on this algorithm. After the introduction of the Ziegler-Nichols rules in the early 40s, the popularity of PID controllers grew exponentially, uncovering enormous applications including ship steering control. The first commercial use of proportional-derivative (PD) control was first mentioned in Luke (1960). It shows that the correct combination of both proportional and derivative terms could ensure reasonable control of the vessel. From the 1950s to date, almost all ship autopilots were based on PD/PID controllers. Conventional PID tuning techniques such as Ziegler-Nichols method, Cohen-Coon, pole placement etc. do not provide good tuning. The solution found with these classical methods only satisfies the performance criteria for a particular model. Therefore, conventional PID is not suitable for shifting operating regions in time varying process. Also, the conventional PID tuning methods such as Cohen-Coon (C-C), Gain-phase margin (G-P) and Internal model control (IMC) methods involve complex numerical computations to obtain controller gain values. The complex computation leads to improper PID settings and provides poor closed loop performance. There is also a tendency of pushing the system close to instability (Kaliappan & Thathan, 2015).

In view of the aforementioned challenges, the quest for some efficient methods to determine the optimized values of the PID controller parameters has become an active area of research. The meta-heuristic approaches reported by Gaing, (2004) are used for the proper tuning of PID controllers in the complex process control. The genetic algorithm (GA), artificial bee colony (ABC), particle swarm optimization (PSO) and ant colony optimization (ACO) are some of the meta-heuristic optimization techniques widely preferred to find the optimum settings of PID (Rajinikanth & Latha, 2012). Also, with the development in computational methods, several intelligent optimization algorithms have been proposed for the tuning of PID control parameters in order to obtain optimal performance (Yan & Li, 2011). Some of these include PSO (Solihin *et al.*, 2011), ACO (Jones & Bouffet, 2008), ABC (Varma & Kumar, 2013). In recent years, ABC receives much attention among researchers due to its performance, ease of implementation and simplicity (Karaboga *et al.*, 2014). ABC uses minimum number of algorithm parameters (colony size (Cs), maximum iteration count (Mi) and limit of trail (T)) than GA, PSO, and ACO. Over the years, research efforts on ABC, have shown that, it provides better PID tuning than other meta-heuristic techniques such as GA, ACO and PSO (Kaliappan & Thathan, 2015). Artificial Bee Colony algorithm is a swarm optimization algorithm, which was inspired by the foraging behaviour of swarms of honeybee. In this algorithm, the bee swarm mainly consists of three components: the employed bees, the onlooker bees, and the scout bees. The employed bees are used to search neighbour food sources (new PID gain values) which is having high nectar value (fitness value) and take the

information about the quality of the food and location to the waiting bees (onlooker bees). The scout bee is responsible for random searching of new food sources (Karaboga & Basturk, 2008).

**MATHEMATICAL MODEL OF THE SHIP**

This subsection deals with review of fundamental concepts that are of paramount importance to this research work. These include the following sub-headings.

**Ship course control**

The major task of a navigator conducting a ship is to assure its proper, safe and efficient navigation (Pietrzykowski & Magaj, 2012). This depends on the amount of information available to the navigator. The more the information available on board the better for the crew in assessing the current navigational situation and making the right decision. On the other hand, too much information may lead to human errors, resulting from difficulties in processing the available data, some of which may not be taken into consideration while a decision is being taken. Therefore, systems of automatic determination of ship’s safe trajectory may be essentially helpful to the navigator (Pietrzykowski & Magaj, 2012).

During navigation, the autopilot system is usually used for leading the ship along the desired course through automatic changes in the rudder blade deflection (Tomera, 2010). An autopilot automatically manipulates the rudder to decrease the error between the reference heading angle and the actual heading angle (Sethuramalingam & Nagaraj, 2015). The motion of a ship is highly influenced by approaching waves and, consequently, the ship, which always sails in the presence of waves, will behave differently from that defined for calm water (Tomera, 2010). Ship’s behaviour in different environmental conditions can be predicted using mathematical models developed to model kinetic movements of the ship and the dynamics of the phenomena taking place (Fang & Luo, 2005). Figure 1 shows the diagram of the proposed cascade control system.

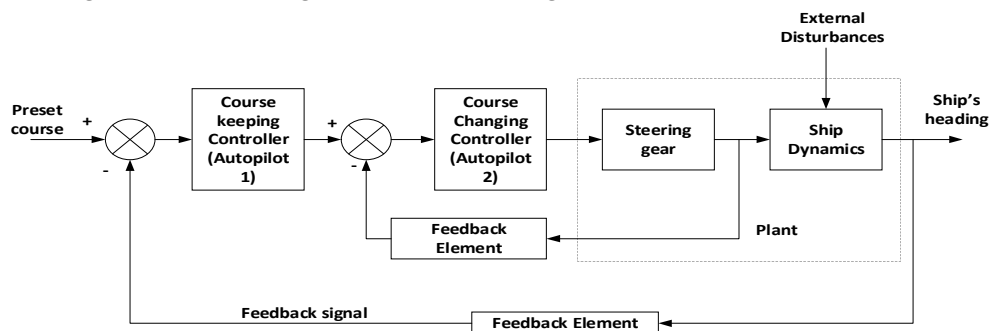


Figure 1: Block Diagram of the Proposed Cascade Control System.

The cascade control system block diagram of Figure 1 shows a control system with two PID controllers, two feedback elements, a steering gear and the plant (ship).

- I. Pre-set course is the desired heading of the ship preselected, by the helmsman or navigator or the course laid out in the voyage plan.
- II. Ship’s heading is the actual heading of the ship.

- III. The steering gear consists of two electrohydraulic steering subsystems: the telemotor position servo and the rudder servo actuator. The input to the steering machine called the commanded rudder angle originates from the autopilot, while the output is the actual rudder angle.
- IV. The inner loop controller (autopilot 2) controls and stabilizes the ship during course changing manoeuvres. The output of the controller is the commanded rudder angle.
- V. While the outer loop controller (autopilot 1) controls and stabilizes the Ship during course keeping manoeuvre. The controller keeps the ship on course by minimizing rudder deflection.

### Course-keeping

The course-keeping mode is nearly always used during navigation. When there are no traffic obstacles in the vicinity, the major concern is minimization of propulsive losses due to steering without harmful yawing (Arie *et al.*, 1986).

### Course-changing

When sailing in restricted waters, course changes are necessary to give way to, or avoid collision with other ships. In these situations, safety is most important (Arie *et al.*, 1986). It is desirable that manoeuvres be carried out in a predictable way, independent of variations in the ship's dynamics. During course changing manoeuvre, a steady and consistent turning rate is usually desired. It is also desirable to turn to the new heading with a constant rate of turn, or possibly with a constant turning radius (Van Amerongen, 1982). The new heading should be reached without overshoot. The possibility to adjust the rate of turn is the only setting required by the user (Van, 1984). Figure 2.4 shows a typical course-changing manoeuvre.

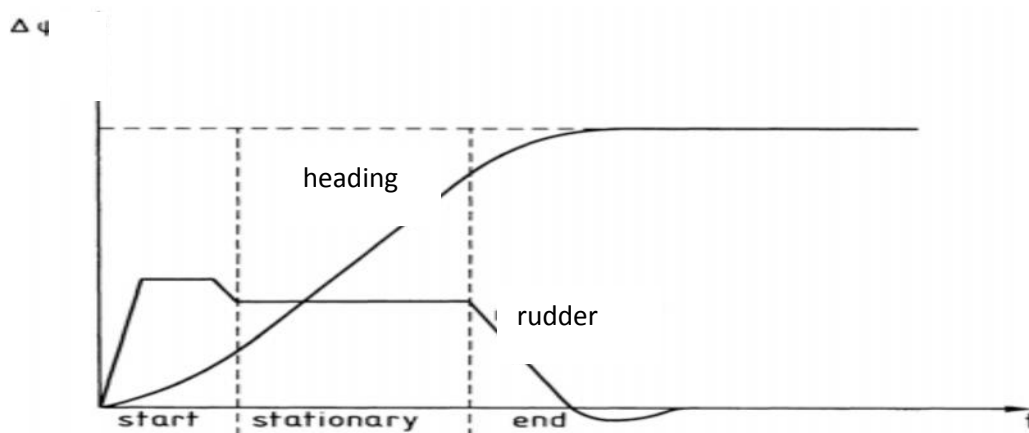


Figure .4: Course-Changing Manoeuvre (Van, 1984)

The three phases in course changing manoeuvres are:

- I. Start of the turn
- II. Stationary turning ( $\dot{\psi} = 0$ )

### III. End of the turn.

To realise a good controller response, adjustment of the conventional controller settings is required, for instance when the ship's dynamics change or when another rate of turn is selected (Van, 1984).

### **Gyro compass on ships**

A gyro compass is widely used on ships to find the true north. Autopilot is synchronised with the gyro compass to steer manually input courses, with reference to the gyro heading (Weintrit, 2009). Furthermore, modern autopilot systems are also capable of being synchronised with the electronic chart system (ECDIS) enabling the ship to follow the courses laid out in the voyage plan. This feature cuts out the need of manual course changes and alterations as the system will follow the courses and alterations as per the voyage plan (Bok & Wright, 1952).

The ability of the gyrocompass to detect the direction of true north and not the magnetic north has made it one indispensable instrument in almost all ships or naval vessels.

### **Ship motion**

The motion of a sailing ship is defined by the six degrees of freedom experienced by the vehicle (Lewis, 1988):

#### 1. *Linear motion*

Linear motion is a motion along a straight line and there are three types of movement associated with ships linear motion (Lewis, 1988):

- a. Heave: is the linear vertical (up/down) motion. Excessive downward heave can swamp a ship.
- b. Sway: is the linear lateral (side-to-side or port-starboard) motion. This motion is created directly by the water and wind currents exerting forces against the hull or by the ship's own propulsion or indirectly by the inertia of the ship while turning. This motion can be compared to the vessel's drift from its course.
- c. Surge is the linear longitudinal (front/back or bow/stern) motion imparted by maritime conditions.

#### 2. *Rotation motion*

Rotational motion is the motion around an object's center of mass where every point in the body moves in a circle around the axis of rotation. There are three special axes in any ship, called vertical, lateral and longitudinal axes and the movements around them are known as roll, pitch and yaw (Lewis, 1988):

- a. Pitch: is the up/down rotation of a vessel about its lateral/Y (side-to-side or port-starboard) axis. A deviation from normal on this axis is referred to as 'trim' or 'out of trim'.
- b. Roll: is the tilting rotation of a vessel about its longitudinal/X (front-back or bow-stern) axis. A deviation from normal on this axis is referred to as list or heel. Heel refers to an offset that is intentional or expected, as caused by wind pressure on sails, turning, or other crew actions while list normally refers to an unintentional or unexpected offset,

caused by flooding, shifting cargo, etc. The rolling motion towards a steady state (or list) angle due to the ship's own weight distribution is referred in marine engineering as heel.

- c. Yaw: is the turning rotation of a vessel about its vertical/Z-axis. A deviation from normal on this axis is referred to as deviation or set.

Figure 2.5 illustrates the six degrees of freedom of ship motions.

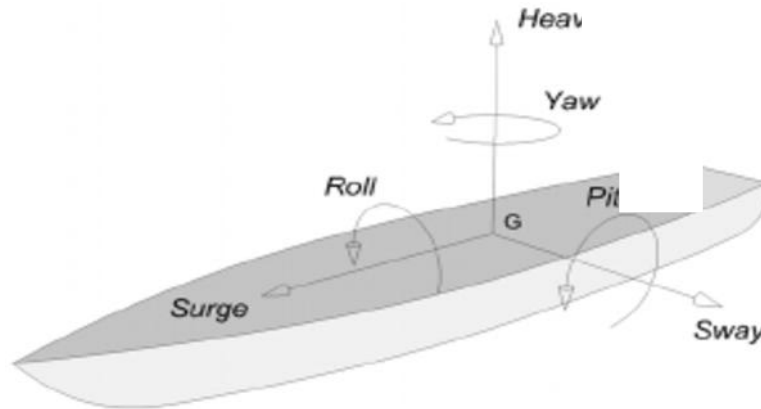


Figure 5: Six Degrees of Freedom Ship Motion (Sandurawan *et al.*, 2011)

### MATHEMATICAL MODELLING OF SHIP DYNAMICS

The ship's center of gravity *G* is chosen as the origin of this ship-fixed coordinate system and the axes of symmetry are chosen as *x*-, *y*- and *z*-axes (Van Amerongen, 1982).

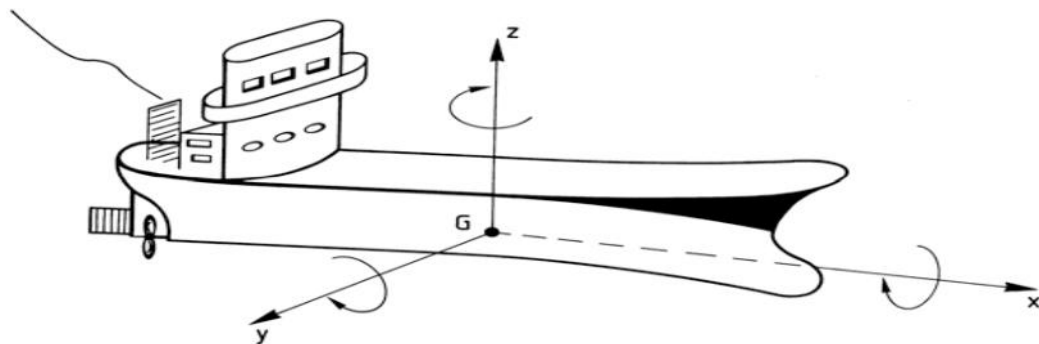


Figure 7: The Ship-Fixed Coordinate System (Van Amerongen, 1982).

In the most general case, there are six degrees of freedom in ship, which are motions in the *x*-, *y*- and *z* directions as well as rotations around these axes. However, for surface ships, it is common practice to consider only motions in the horizontal plane and this reduces the number of degrees of freedom to three (Lim, 1980):

- Motions in the *x*-direction ('surge')
- Motions in the *y*-direction ('sway')
- Rotations around the *z*-axis ('yaw')

Figure 8 depicts the coordinates and variables that play a role in the modelling process.

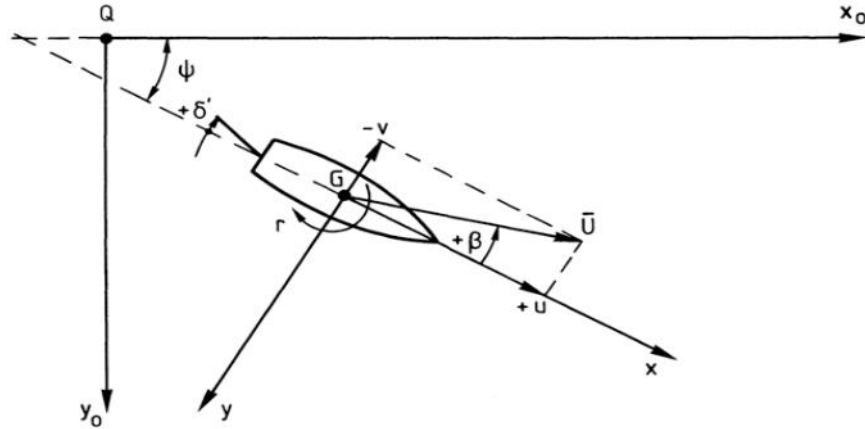


Figure 8: Definition of Motions in the Horizontal Plane (Witkowska *et al.*, 2007)

The basic equations of motion are obtained by writing Newton’s laws in a space-fixed coordinate system.

$$m \frac{d^2 x_0}{dt^2} = X_0 \tag{1}$$

$$m \frac{d^2 y_0}{dt^2} = Y_0 \tag{2}$$

$$I \frac{d^2 \Phi}{dt^2} = N \tag{3}$$

Transformation of equations (1.1) - (1.3) yields

$$m(\dot{u} - vr) = X \tag{4}$$

$$m(\dot{v} + ur) = Y \tag{5}$$

$$I_{zz} \dot{r} = N \tag{6}$$

Where,  $X$  and  $Y$  are the summations of all the forces in the  $x$ - and  $y$ -directions, which act on the hull of the ship and  $N$  is the moment caused by these forces. It is not easy to determine the relationship between  $X$ ,  $Y$  and  $N$  and all the variables involved (Van, 1984).

Expansion of equations (1-6) into a Taylor series and the introduction of non-linear terms yield a much more complex model. These complex models which are popular among naval architects can accurately predict the motion of a ship in a sea way. However, the determination of the large number of parameters in these models must be repeated for different ships and the techniques rely heavily on scale model testing which undoubtedly creates further problems with regard to scaling. An alternative approach is to refine the model into a form recognisable by control engineers (Nomoto *et al.*, 1956).

### PID Controller

In spite of the presence of many modern controllers, many industrial processes are controlled using (PID) controllers. Thus, the PID controller is viewed as the backbone of the process

control. The popularity of these controllers can be attributed to their good performance in a wide range of operating conditions, simplicity with few parameters, which allows engineers to operate them in a simple, robust and straightforward manner (Bassi *et al.*, 2011). In many industrial process control applications, application of only proportional control is unsatisfactory since the offset cannot be eliminated. The PI controller is probably the most common controller, and is adequate when the dynamics of the process are essentially first or damped second order while PID is commonly used when the dynamics are second or higher order (Åström, 2000; Åström & Hägglund, 2001). In practice, the output of a PID controller is given by Bansal *et al.*, (2012):

$$u(t) = K_p \times e(t) + K_i \times \int_0^t e(t) dt + K_d \times \frac{de}{dt} \quad (7)$$

$K_i$  and  $K_d$  can be written as:

$$K_d = K_p \times T_d, \quad K_i = K_p \times \frac{1}{T_i}$$

$$u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \quad (8)$$

$$G(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s$$

(1.26)

$$G(s) = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right) \quad (9)$$

In equations (8) – (9),  $K_p$  is the proportional tuning constant,  $K_i$  is the integral tuning constant,  $K_d$  is the derivative tuning constant,  $T_i$  is the integral time,  $T_d$  is the derivative time,  $G(s)$  is the transfer function of the system and error  $e(t)$  is the difference between the set-point and the process variable at a time.

## REVIEW OF SIMILAR WORKS

Witkowska *et al.* (2007) presented the design of nonlinear ship course controller using the back stepping method. The parameters of the obtained nonlinear control structures are tuned to optimize the operation of the control system. The optimization was performed using GA. In order to obtain reference results for comparison with those recorded for nonlinear controller designed using the back stepping method, a control system with PD controller was examined as well. However, the back stepping method requires precise information on the model of the examined system and its varying parameters, which is extremely difficult in practical applications. Ghaemi *et al.* (2010) presented a model predictive control (MPC) strategy for path following on a model ship. The MPC was designed and implemented using both linearized and nonlinear model and the implementation was performed experimentally via integrated perturbation analysis and sequential quadratic programming (InPA-SQP) algorithm. The effectiveness of the proposed MPC was verified



with experimental results. However, the implementation of MPC technique remains fundamentally limited in systems with fast and/or nonlinear dynamics, due to high demand in computational resource associated with optimization.

Shih et al. (2012) proposed the design of optimal control of ship manoeuvre patterns for collision avoidance. Since an overall model to control of ship manoeuvring in a natural environment for all type of ships has not been designed, because there are so many factors that will affect the formulation, the aim of the research was to develop a nonlinear unified state-space model, joined with another approach according to the requirements of the situation. Other works on optimal turning and ship manoeuvring for collision avoidance were reviewed. Different approaches depending upon different practical purposes and areas have also been defined. Tsou and Cheng (2013) presented an ant colony algorithm for efficient ship routing. In this work, a route searching model was established using a proper grid system and improved ACA. In addition, GA's crossover and mutation computations, a ship's critical speed function, and GIS's spatial analysis and computation capability were integrated to automate the generation of a transoceanic crossing route, in consequence increasing route planning speed and quality, and lowering the ship crew's burden. Besides the realization of route planning automation, ship routing will achieve the goal of optimum carbon dioxide reduction and energy conservation, and provide reference for route planning decision. However, the experimental measures for the division of the marine grid system are based on the North Atlantic Ocean from Western Europe to North America and this may not be applicable to other marine areas.

Tomera (2014) described the application of an ant algorithm to optimize parameters of the ship course controller, based on the algorithm of PID control. The effectiveness of PID controller parameter tuning was assessed using the ant colony optimization algorithm. The procedure of parameter tuning for the ship course controller was applied to the case when the controller was changing the course of the ship and the integral action was turned off. Tuned parameters of the ship course controller were obtained by the ant colony algorithm, which makes use of the course error based objective function and a given rudder deflection. The results obtained were compared with equivalent results obtained using genetic algorithm. However, the research did not consider ship course changing. This limitation will limit the application of the controller.

Lazarowska (2015) presented an application of the Ant Colony Optimization (ACO) technique in a safe ship control system. The method developed solves the problem of path planning and collision avoidance of a ship in the open sea as well as in restricted waters. The structure of the developed safe ship control system is introduced, followed by a presentation of the applied algorithm. The aim of the system developed is to increase automation of a safe ship control process. The analysis of simulation results showed that despite the application of a stochastic optimization method, the algorithm provides reproducible solutions. However, the research does not take into account the strategies of the target ship. It was assumed that the target ship does not change its course and speed. This assumption can affect the practical application of this research.

Sethuramalingam and Nagaraj (2016) presented a proposed system of ship trajectory control using particle swarm optimization. In this work, PSO optimizes a fuzzy model reference learning controller (FMRLC) for ship control. The FMRLC was developed by synthesizing several basic ideas from fuzzy set and control theory. It was shown that PSO can provide a very promising

technique for the design of FMRLC for its simplicity and ease of use. The results from the experiment provide direct evidence for the feasibility and effectiveness of PSO for the optimization of FMRL controller for ship heading regulation. It was shown that the fuzzy controller is continually updated in response to ship parameters variations or wind disturbances. However, the computing time for FMRLC was long, because of the complex operation such as fuzzification and particularly defuzzification. Also, when system that is more precise is required, tuning fuzzy controllers may take a lot of time, perhaps even more than a conventional controller. This can in turn affect the ship steering system response time.

## METHODOLOGY

Development of an ABC-based PID for ship course control.

- i. Initialization of the parameters that is population size, maximum iteration and creation of initial population.
  - ii. The employed bees are moved onto their food sources and determine their nectar amounts.
  - iii. The onlooker bees are moved onto their food sources and determine their nectar amounts.
  - iv. The scouts were saddled with searching for new food sources
  - v. The best food source found is memorized until the requirements are met.
  - vi. Implementation of the ABC-based PID Controller
1. Comparison of the performance of the developed ABC-based controller with the work of Tomera et al, 2014.
    - i. Implement the ship course in MATLAB environment.
    - ii. Apply the ABC-based PID, ACO-based PID and GA-based PID for the ship course tracking.
    - iii. Comparison of the performance of the three controllers using steady state, overshoot and settling time.

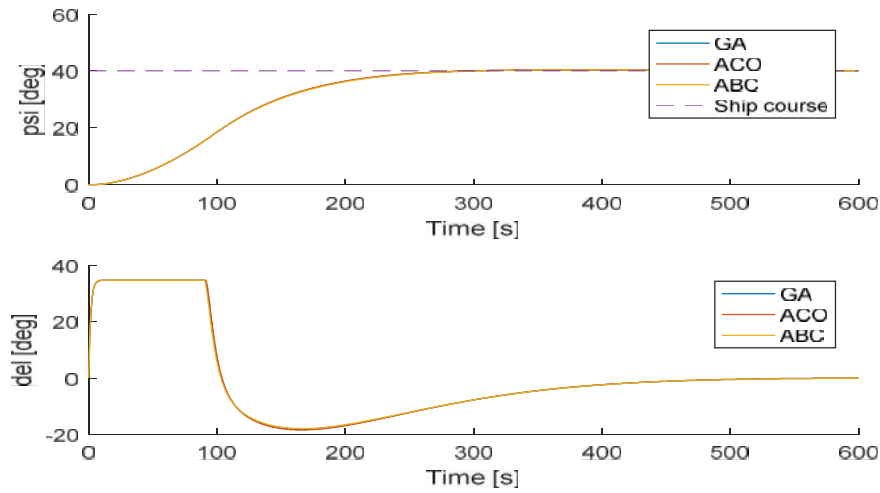
## DISCUSSION OF RESULT

### ***Performance evaluation of ABC-based PID controller and ACO-based PID controller.***

The comparison is carried out between ABC-based PID controller and ACO-based PID controller for various values of PID gains in terms of settling time, maximum overshoot and rise time.

### ***Comparison of ABC-based PID controller, ACO-based PID and GA-based PID controller Performances.***

The comparison is carried out between ABC-based PID controller and GA-based PID controller for various values of PID gains in terms of settling time, maximum overshoot and rise time.

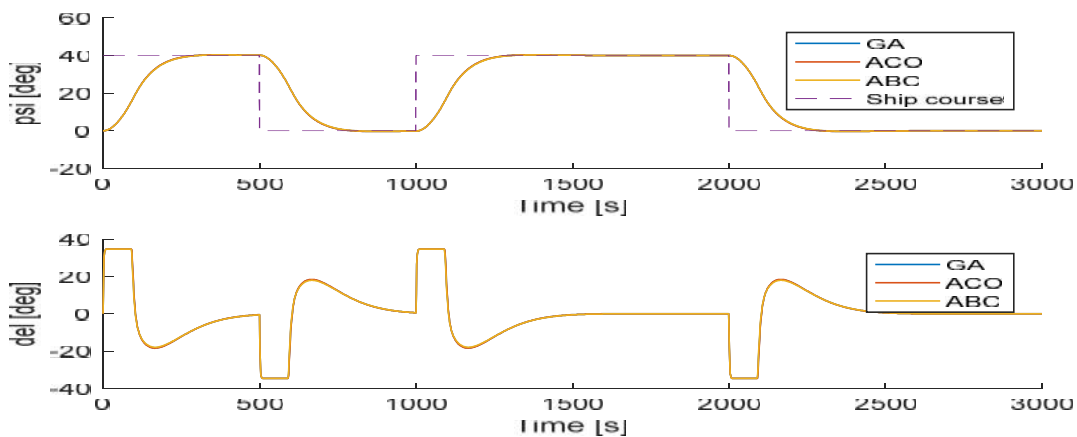


**Figure 9:** Comparison of ABC-based PID controller, ACO-based PID and GA-based PID controller Performances for course changing.

**Table 1:** Comparison between Genetic Algorithm, Ant Colony Optimization and ABC-based PID controller for course changing.

	G.A	ACO	ABC
Tr	152.9007	152.0754	154.7535
Mp	0.7263	0.7424	0.6538
Ts	257.9482	256.4693	261.8709
JE	9.1779	9.1728	8.9777

From the table 1, it is obvious that ABC Algorithm outperforms the GA algorithm and ACO algorithm respectively in terms of the performance index. Figure 9 illustrated the time indicator quality of the rise time, settling time and the overshoot, it was found that the ABC algorithm has the optimal performance index of 8.9777 as compared to that of G.A and ACO which was 9.1779 and 9.1728 respectively, with a maximum overshoot of 0.6538.



**Figure 10:** Comparison of ABC-based PID controller, ACO-based PID and GA-based PID controller Performances for course tracking.

Table 2: Comparison between GA, ACO and ABC-based PID controller for course tracking.

	G.A	ACO	ABC
Tr	0.4007	0.3963	0.3934
Mp	$1.5799 \times 10^7$	$1.6309 \times 10^7$	$1.6627 \times 10^7$
Ts	$2.2560 \times 10^3$	$2.2546 \times 10^3$	$2.2598 \times 10^3$
JE	7.0184	7.0088	7.0377

From figure 10 and table 2 above, it can be seen that ACO algorithm outperforms the G.A and ABC algorithm in terms of the performance index, ACO algorithm has the optimal value of 7.0088 for the performance index with a minimal rise time of 0.3963s, settling time of  $2.2546 \times 10^3$ s and maximum overshoot of  $1.6309 \times 10^7$  respectively. For the course tracking of the ship tanker, ACO algorithm tracks better when compared the other two algorithms.

## CONCLUSION AND RECOMMENDATIONS

This paper presented the performance evaluation of an ABC based PD controller for tanker ship steering control. The mathematical model of tanker ship base on the work of Witkowska et al. (2007) was obtained and implemented. A PD controller based on the obtained model was developed. The artificial bee colony algorithm was used to optimize the proportional differential gains of the PD controller. The technique was implemented in Matlab R2015b and simulation results have been presented and efficient conclusion made. For the purpose of comparison, the work of Tomera (2014) was replicated.

The performance of the developed ABC based PD controller was compared with GA and ACO based PD controllers. ABC algorithm can be hybridized with another meta-heuristic algorithm and used for the tuning of the PD controller parameters. The optimized controller will then be applied for the ship control. Since the system is non-linear, a non-linear controller can be used for the ship steering control and a modified ABC algorithm can be used in tuning the PD controller in order to achieve better tuning of the controller. The modified ABC based PD controller can therefore be used in controlling the ship

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